Experimental Investigation on Flat Plate Solar Collector with Integrated Wickless Heat Pipe

دراسة عملية على مجمع شمسي نوع فلات بليت باستخدام الانبوب الحراري

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بحث مستل من رسالة ماجستير

Abstract

An experimental study is carry out to investigate the effectiveness of a flat plate solar collector (FPSC) through replacing the riser tubes by integrated wickless heat pipe (WHP) heat exchanger. The study show the effect of working fluid filling charge of the WHP, the tilt angle, and inlet coolant temperature on the solar system performance. A FPSC with area of (0.76*0.96) m^2 built with copper WHP of 19mm evaporator tubes outer diameter and single horizontal condenser of 28mm outer diameter using distilled water with (40, 60, and 80) % filling ratios as a working fluid inside the WHP. The collector efficiency was directly affected by the filling ratio of the WHP while tilt angle is contributed to solar radiation more than WHP performance.

Keywords: flat plate solar collector, integrated heat pipe, fill ratio.

الخلاصة

دراسة عملية للتحقق من فعالية المجمع الشمسي ذو اللوح المسطح من خلال استبدال الانابيب الناقلة بأنبوب حراري (بلا فتيلة) متكامل كمبادل حراري. تظهر الدراسة تأثير نسبة ملئ مائع التشغيل في الانبوب الحراري، زاوية الميلان، ودرجة حرارة الدخول لمائع التبريد على اداء المنظومة الشمسية. تم تصنيع المجمع الشمسي بمساحة (0.96*0.76) م2 مع انبوب حراري من النحاس بقطر خارجي للمبخر 19 ملم وانبوب افقي كمكثف بقطر خارجي 28 ملم واستخدام الماء كمائع تشغيل داخل الانبوب الحراري بنسب ملئ (40,60,80) % . وجد ان كفاءة المجمع تتأثر بشكل مباشر بنسبة ملئ مائع التشغيل للأنبوب الحراري بينما زاوية الميلان تتأثر بشدة الاشعاع الشمسي اكر من اداء الانبوب الحراري.

Table of symbols

Symbol	Definition	Units
A_c	Collector area	m^2
c_p	Specific heat	Kj/Kg.C
I	Incident radiation	W/m^2
M	Mass flow rate	Kg/sec
Q_u	Useful heat	W
R	Thermal resistance	C/W
FPSC	flat plate solar collector	
FR	Filling ratio	
WHP	Wickless Heat Pipe	
ΔT	Temperature difference	C
η	Efficiency	

Introduction

One of the simplest design and installation of the solar applications is the FPSC which has a wide interest of researches for its high efficiency as comparison with its low initial cost and high flexibility for building and development.

Many research's referred to insert the heat pipe, which is a passive efficient heat transfer device, to solar applications for its low thermal resistance and high heat transfer rate at low temperature gradient between it ends connected to the heat source and heat sink[1].

The different between the natural circulated flat plate solar collector and that worked with heat pipe is with the first type the heat extracted by the fluid directly from the risers but the second type the fluid extract heat from a heat exchanger between represented by heat pipe condenser section.

Some advantages and disadvantage observed from the literature where S. M. Khairnasov and A. M. Naumova[2] study the heat pipe application to a solar system and find there is many types of heat pipe can be used in solar application to each one its advantages and disadvantages but all types add a new thermal resistance to the solar system.

So that adding a heat pipe should increases efficiency or give a simplicity in assembly or other benefits to compensate its additional thermal resistance also it find that Thermosyphon has less thermal resistance than other heat pipes.

A. Ordaz-Flores, et al. [3] made a comparison between natural circulated Thermosyphon flat plate collector and two phase close Thermosyphon system with the same geometry and conditions but the close system reject heat by a coil condenser heat exchanger contained by storage tank. R134a and acetone were used as working fluids. The R134a close cycle Thermosyphon show better results in addition of some advantage like avoiding freezing, corrosion, fouling, and scaling problems.

E. Azad[4, 5] a flat plate collector with 6 copper heat pipe was investigated theoretically and experimentally. A theoretical model developed suggest the evaporator to condenser length, the collector efficiency, and the temperatures of water and heat pipe.

The experimental data shows concurrence with that absorbed theoretically. Later Proposed a comparative method for testing flat plate solar collectors with different shape to absorb and extracted heat by installed them in parallel positions and integrated the heat pipes as a single heat pipe.

A three collectors the first one with fins as absorber connected with the evaporator zone and (shell and tube) heat exchanger in the condenser zone for extracting heat to coolant the second shape of plate absorber and double pipe heat exchanger the third shape with flat plate absorber also but with shell and tube heat exchanger.

Result of calculating collector's efficiency at different incidents shows that the first shape with find absorber has the higher efficiency.

Rassamakin, et al. [6] design and manufacture integrated absorber aluminum plate grooved with longitudinal internally finned heat pipe (finned surface play a role similar to wick structure). And test it laboratory at different inclined angles from 0 to 90^0 for checking thermal resistance and maximum heat transfer.

It found that heat pipe at angles from 5^0 to 90^0 have higher heat transfer than at horizontal position since it work as a Thermosyphon and there is low thermal resistance between pipe and plate as they work as single structure.

Ling Jiao, et al. [7] experimentally tested an integrated WHP for a flat plate collector with 15 copper tube connected by two horizontal tubs and a single liquid return tube, it was filled with 50% ethanol as a working fluid. The collector inclined 60^0 from horizontal and the heat pipe solar system connected to a storage tank filled with 200 kg of water. Experimental test was take from 9 am to 4 pm in the outside environment conditions. 66% was the maximum efficiency of the collector while storage tank temperature increased by 25 ^{0}C. In the present work the FPSC investigated experimentally with integrated WHP to improve its efficiency and showing the working fluid fill ratio effect on its performance.

Experimental apparatus

The FPSC is featured by its simple design and manufacturing. It majorly consist of: casing, insulator, transparent cover and, energy absorber plate. The casing ensures stability and protects the absorber and the insulation against environmental impacts.

In the present work the box of collector was made from wood since it's simply to manufacturing, low weight, low thermal conductivity, low cost and, suitable for experimental rig testing. It was fabricated locally with a benefit of easily installing and remove the WHP and the transparent cover, by made it as rectangular box of (96x78x10) cm with a stream at the upper side to slide the glass in and out of the collector, also by drilling a holes in the top wall and made it moveable easily. The casing box bottom end set on a movable base while the top end connected with the base by a variable length and replaceable pedestal for the purpose of changing the angle of inclination.

The insulation around the collector bottom and edges are so important to improve the heat to be lost by the conduction mode. So having a good insulator may be prevent any heat to be lost.

The glass-wool found suitable for this purpose since it's dimensionally and chemically stable at high temperatures, and resistant to weathering and dampness from condensation, also to its low thermal conductivity of 0.04 W/m.C. A two layers of (2.5 cm) thick each was hold inside the casing box bottom and edges.

A smooth window glass of 4 mm thickness with a transmittance of (0.9) was chosen as a transparent cover as it's recommended in many literature researches.

Also aluminum plate was selected as the absorber plate with thickness of 1mm. The flat plate was pressing to have a shape which give more contact between the plate and WHP evaporator tubs. Also it was coated by non-reflected black color to improve its emissivity, then it holed in the casing box.

A WHP is consist of a container include a working fluid inside it works in the principle of latent heat of vaporization as it divided into evaporator section connected to the heat source and condenser section reject heat to a heat sink. The two sections separate by an adiabatic zone**[8]** as shown in Fig.1.

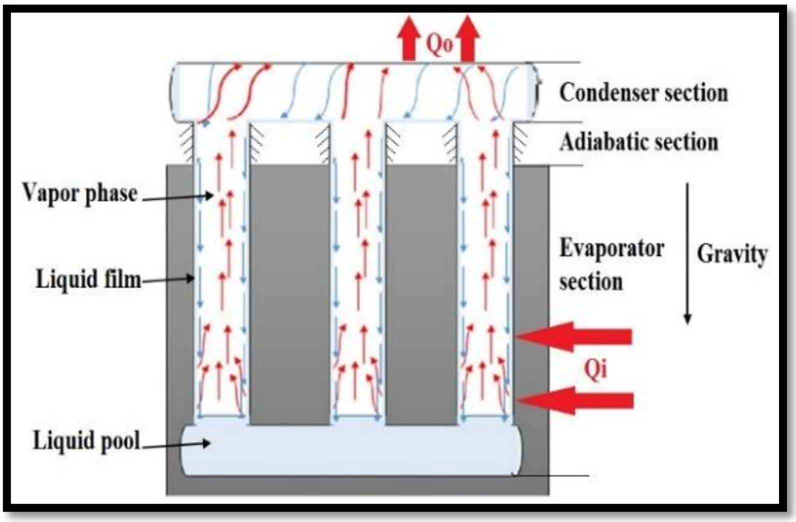

Figure 1: WHP principal work

The WHP was made of copper with 12 tubes of 100 cm length and 1.7 cm internal diameter connected together from the bottom by elbows and T-section joints to function as single evaporator which give better distribution of working fluid between the tubes and made the collector work on approximately isothermal temperature distribution.

The tubes connected from the top side by a single tube has larger diameter (2.54 cm) as condenser section and rounded by other tube to form a double pipe heat exchanger between the condensate vapor and the coolant fluid. Also two valves welded at bottom and top of the WHP for vacuum and charging proses.

The WHP is vacuumed using a vacuum pump type value (model VE115N) 1 stage 2 CFM to lower the saturation temperature of the distilled water. The experimental rig setup is shown in Fig.2.

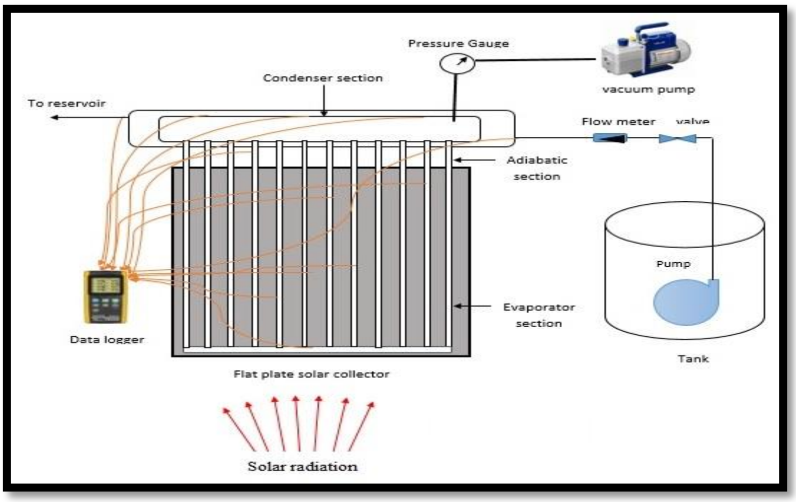

Figure 2: experimental rig setup

Experimental measurements and test procedure

The temperature distribution on different location of WHP solar system measured by thermocouples wire type K with semi spherical head was used to contact with grooves made on the WHPs surface and at plate, inlet, and outlet of coolant measuring the required temperatures. The thermocouples locations shown in Fig.3, and connected by other side to a 12 channels temperature recorder (BTM-4208SD) with accuracy = ± 0.4%, Resolution=0.1°, Reading temperature range of -100 ºC to max. Temperature of 1300 ºC.

The incident power radiation on the collector is measured by a solar power meter type (TES 1333R) with a range changed from (0 to 2000 W/m^2), with resolution of 0.1W/m^2, accuracy ±10W/m^2, and medium temperature range from (0 to 50 ^{0} C). The constant flow rate of coolant measured by a flow meter Sp.Gr.1.0.

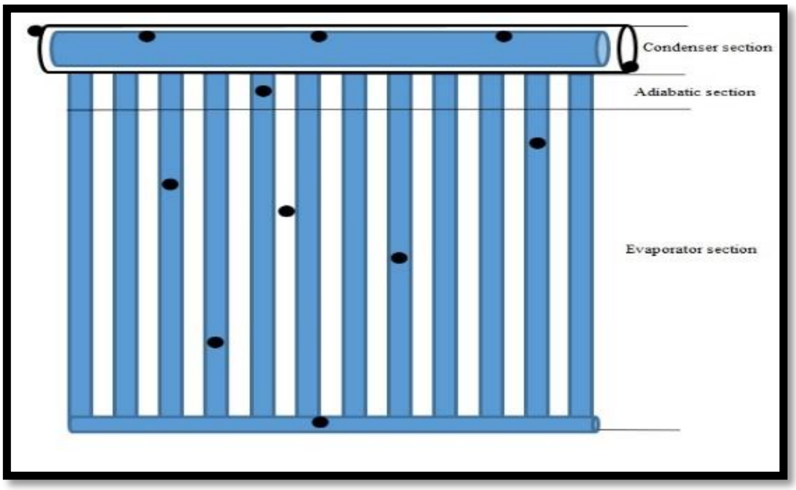

Figure 3: thermocouples locations

At the outdoor environment conditions of Iraq-Karbala University of Kerbala College of Engineering with 32.36° N latitude and 44.1° longitude. The WHP solar system tested at (40, 60, and 80) filling ratios of evaporator internal volume and at three tilt angles of (30, 50, and 70) from the horizontal position and the FPSC orientated to facing the south.

The running test were started at 10:00 am and end at 2:00 pm from 5 to 25 February. And during the outdoor experiments the solar radiation was recorded every 15minutes, while the flow rate of water was kept at 0.65 L/min in open cycle where the inlet temperature doesn't change during the experiment test and the outlet water accumulate at other reservoir.

Then to check the inlet temperature effect on the operating temperature and performance of the WHP solar system the open flow of all the experiments was replaced by closed circulated cycle of water where the FPSC heat exchanger connect to a small size storage tank.

The WHP filled with 40% of working fluid and the FPSC was tilted at an angle of 50^0 from horizontal and orientated to south. The storage tank was well insulated and filled with 10.5 Liter where the water was circulated by the water pump with a flow rate of 1 L/min through insulated piping connection.

The heat gain from the solar system is calculating depending on:

$$Q_u = \dot{m}\, c_p\, \Delta T$$

And the instantaneous overall collector efficiency find from[9]:

$$\eta = \frac{Q_u}{I\, A_c}$$

Results and discussion

1- Temperature distribution

Fig.4 and Fig.5 represent the temperature distribution drawn various the local time for the cases of 40,80 % fill ratio respectively at 70^0 tilt angle on different positions of the FPSC include coolant inlet and outlet temperatures, WHP evaporator, adiabatic, and condenser section temperatures, and absorber plate temperature.

The absorber plat temperature has the higher value and reach maximum at solar noon then starts to fall down. While the WHP work on close temperatures between the evaporator and condenser section, hence the better performance absorbed at low temperature different between WHP ends.

The 40% fill ratio of the WHP operate on lower plate and evaporator temperatures than other fill ratios. From figures the plate temperature of the 80% fill ratio is higher than 40% in spite of the incident radiation when tested the 40% fill ratio was higher. Also the ΔT between evaporator and condenser at the 40% fill ratio is lower than other fill ratios. This mean lower thermal resistance in the axial direction of the WHP since the thermal resistance has directly proportional to the temperature difference as (R=ΔT/Q).

The fill ratio of the WHP effect on the operating temperature more than the effect of change in radiation intensity or tilt angle. Hence the temperature distribution at the other angles show close values to that at 70^0 for the same fill ratio.

A very low temperature difference between the condenser surface and the outlet temperature is notes at all cases which means high effectiveness heat exchanger between condenser surface and coolant flow over it.

2- Useful heat gain and collector efficiency

Figs.6-8 Represent the outdoor resultant useful energy drown with the measured incident radiation multiplied by the collector area (I*A) versus the local time for angles of (30^0, 50^0, and 70^0) respectively at 40% fill ratio.

Comparison between charts clarified that the effect of incident value (as the collector inclined by different angles) on the useful energy is more than effect of WHP performance at different angles. By compared angle 30^0 and 50^0 where they have approximately close incident values and useful energy gain.

Fig.8-10 represent the outdoor resultant useful energy drown with the measured incident radiation multiplied by the collector area (I*A) versus the local time for (40, 60, and 80) % fill ratios at 70^0 inclined angle.

The maximum value is reached at the solar noon as it higher incident radiation after that start to fall down. A steady behavior absorbed when the WHP filled with 40% of the working fluid with high response to the change in solar incident. Conversely results at high fill ratios especially at 80% fill where high fluctuation of useful energy gain at 80% filling ratio is absorbed this due to geyser boiling phenomena at WHP evaporator at high fill ratios same results observed by[10, 11] .

The collector efficiency was study when changing the inclination angles for a specific fill ratio, in spite of lower efficiency at 70^0 but by 2% from other tilt angles. But the different between angles is the amount of heat gain.

In other hand the 40% fill ratio show highest efficiency of 76 % and higher than other filling ratios by 8% as shown in Fig.11.

3- Inlet temperature effect

Fig.12 represents the mean temperature of evaporator and condenser as well as the inlet and outlet temperature of the coolant water circulated with 1 L/min volume flow rate at 40% filling ratio of working fluid and 50^0 inclined angle at the environment conditions at the city of Karbala for range of incident (950-1000) W/m^2.

As the tank temperature increase inlet temperature to condenser section increase, the inlet temperature increase from 11^0C to 50^0C in about one and half hour and according to that evaporator and condenser temperatures increase in a linear behavior as the coolant flow rate constant and incident doesn't change through the experiment by large value.

The temperatures difference between evaporator and condenser as well as the difference between inlet and outlet became constant till the inlet temperature get 45^0C where the ΔT decrease. That because of inlet temperature crossed the saturation temperature which lead to decreasing condenser efficiency. Where chart show that the temperature difference between the outlet and condenser surface increase when inlet temperature arrived 45^0C.

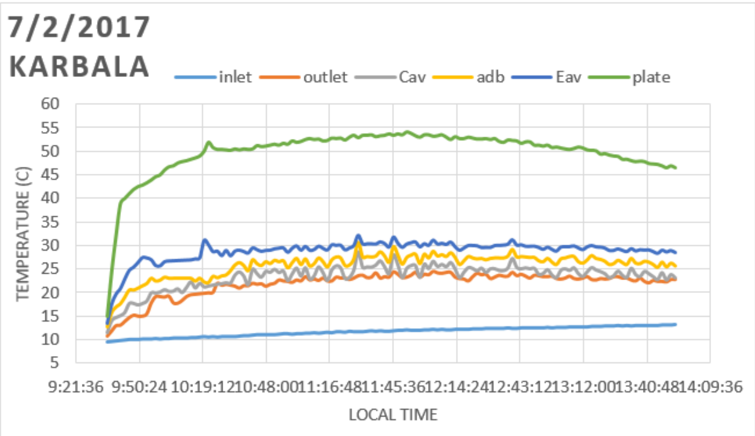

Figure 4: FPSC temperatures at different positions for 40% FR and 70^0 tilt angle

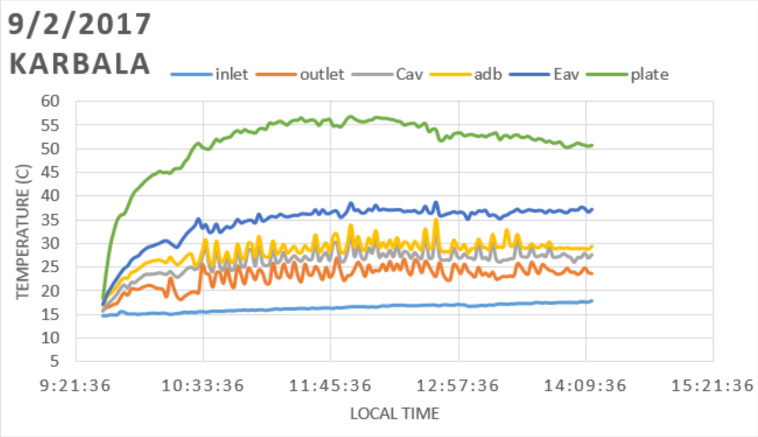

Figure 5: FPSC temperatures at different positions for 80% FR and 70^0 tilt angle

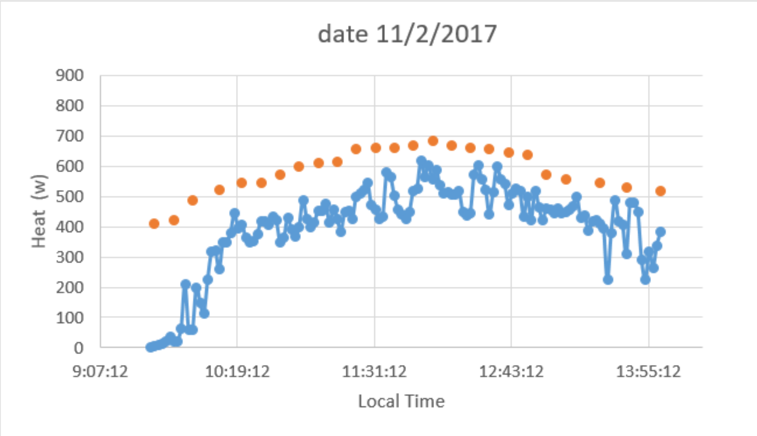

Figure 6: useful energy gain with total incident Radiation (I*A) versus local time at 40% FR and 30^0 tilt angle

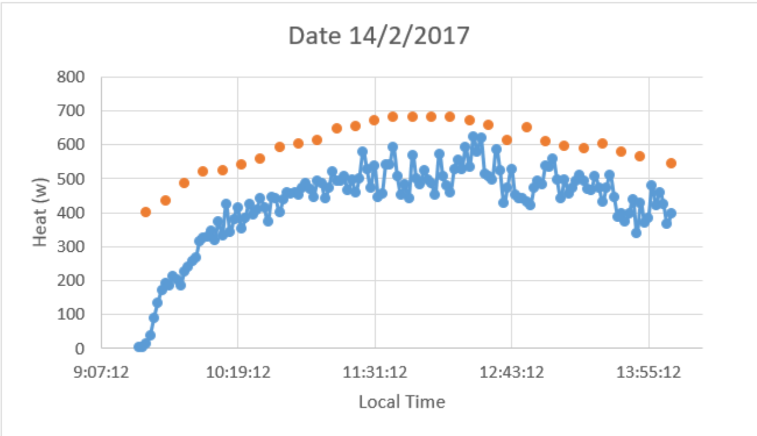

Figure 7: useful energy gain with total incident Radiation (I*A) versus local time at 40% FR and 50^0 tilt angle

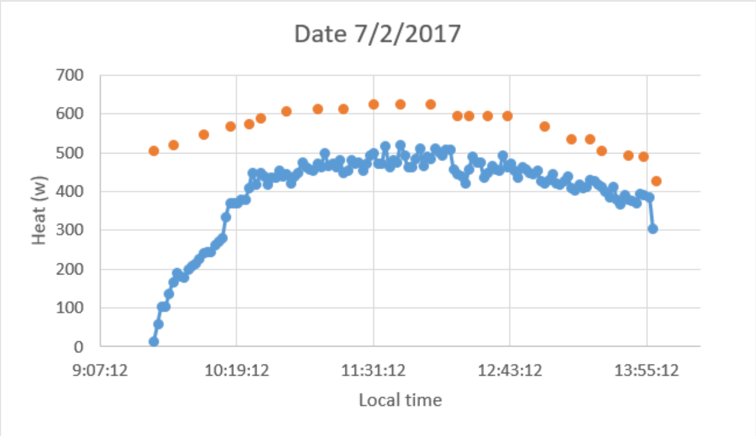

Figure 8: useful energy gain with total incident Radiation (I*A) versus local time at 40% FR and 70^0 tilt angle

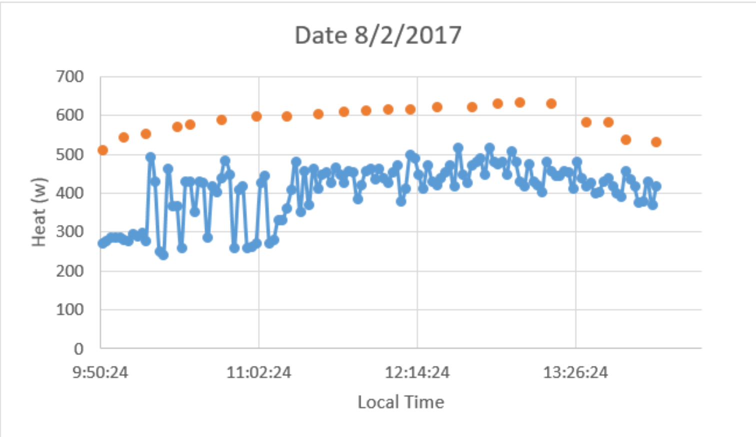

Figure 9: useful energy gain with total incident Radiation (I*A) versus local time at 60% FR and 70^0 tilt angle

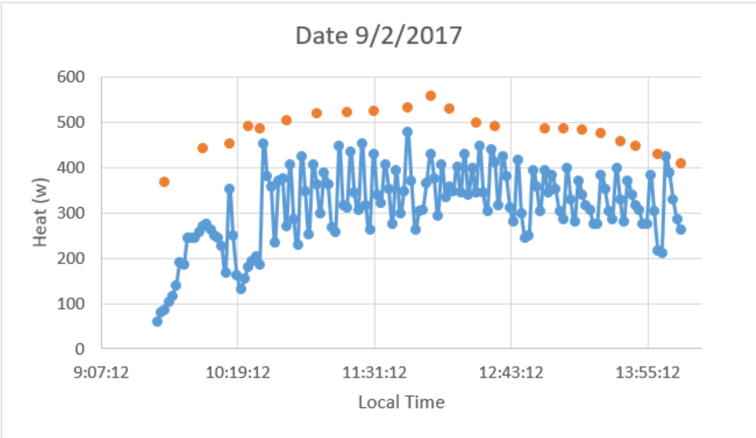

Figure 10: useful energy gain with total incident Radiation (I*A) versus local time at 80% FR and 70^0 tilt angle

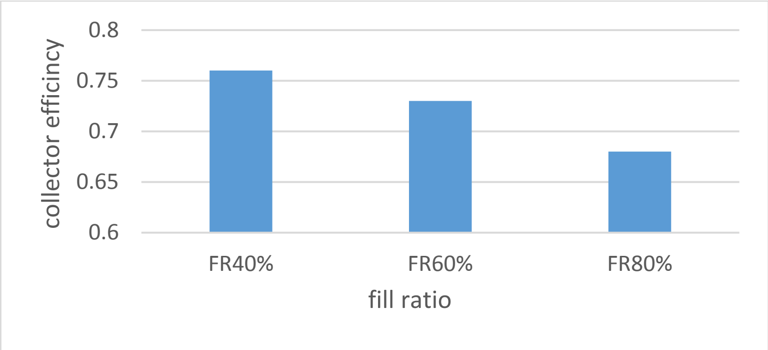

Figure 11: collector efficiency for different fill ratios

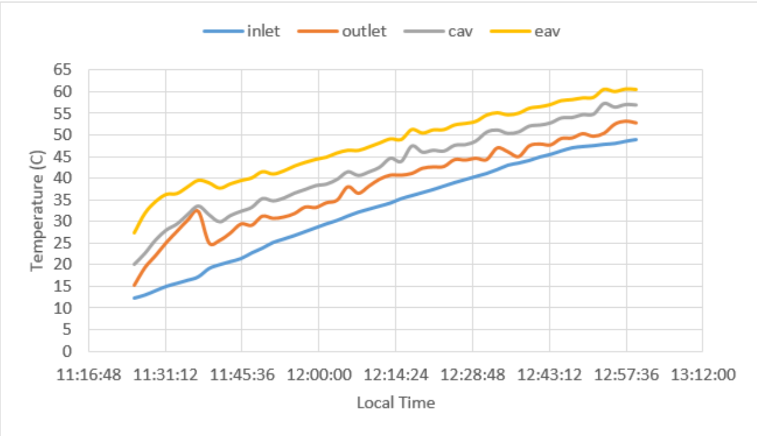

Figure 11: inlet temperature effect on the operating temperature of the WHP solar system

Conclusions

From the above results of testing the FPSC with integrated WHP at the outdoor conditions it can be conclude that relatively high collector efficiency absorbed by using integrated WHP instead of single heat pipes reach to 76 %. And that efficiency affected by the WHP fill ratio more than solar incident and tilt angle of the collector.

And since the efficiency at the same fill remain constant the suitable angle can be recognized by maximum heat gain and maximum absorbed solar radiation. Where 30-50 find suitable for Karbala conditions.

The inlet coolant temperature should be lower than the saturation temperature of the working fluid and for high inlet temperature system pressure should be managed to get the suitable saturation temperature.

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